

# Actively Star Forming Elliptical Galaxies at Low Redshifts in the Sloan Digital Sky Survey

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## ABSTRACT

We report discovery of actively star forming elliptical galaxies in a morphologically classified sample of bright galaxies at a low redshift obtained from the Sloan Digital Sky Survey. The emission lines of these galaxies do not show the characteristics of active galactic nuclei, and thus their strong H $\alpha$  emission is ascribed to star formation with a rate nearly as high as that is seen in typical late spiral galaxies. This is taken as evidence against the traditional view that all elliptical galaxies formed early and now evolve only passively. The frequency of such star forming elliptical galaxies is a few tenths of a percent in the sample, but increases to 3% if we include active S0 galaxies. We may identify these galaxies as probable progenitors of so-called E+A galaxies that show the strong Balmer absorption feature of A stars superimposed on an old star population. The approximate match of the abundance of active elliptical plus S0 galaxies with that of E+A galaxies indicates that the duration of such late star formation episodes is of the order of  $\gtrsim 1$  Gyr. If we interpret these galaxies as new additions to the early-type galaxy population, and if we assume a power law for their number evolution, the abundance of early-type galaxies at  $z = 1$  is about 30% less than that at  $z = 0$ .

*Subject headings:* galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: statistics

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## 1. Introduction

Elliptical galaxy formation has been a key issue in the general theory of the formation of galaxies. It is the traditional view that elliptical galaxies are old systems, which formed at a high redshift, passively evolving until the present without further star formation activity (Eggen, Lynden-Bell & Sandage 1962; Tinsley & Gunn 1976). In recent decades a rival view has been proposed based on the hierarchical structure formation scenario, namely that elliptical galaxies form from major mergers and are relatively young objects (Kauffmann, White, Guiderdoni 1993; Baugh, Cole & Frenk 1996; see also Toomre 1977; Schweizer 2000). While many observations support the old formation scenario for elliptical galaxies at say,  $z > 2$  (Bower, Lucey & Ellis 1992; Terlevich, Caldwell & Bower 2001; Ellis et al. 1997; Fukugita, Hogan & Peebles 1996; Peebles 2001), there are also recent reports indicating that field ellipticals may have formed at rather low redshifts (van Dokkum & Franx 2001; True et al. 2002; Menanteau, Abraham & Ellis 2001). Evidence has also been reported that a small fraction of early-type galaxies retain a signature of star formation that occurred in the recent past (Zabuldo et al. 1996; Quintero et al. 2003; Goto et al. 2003).

In this Letter we present new evidence that a small fraction of field elliptical galaxies show ongoing active star formation with rates as high as those in spiral galaxies. The reason that such objects were not previously known may be due to the fact that both a sufficiently large spectroscopic elliptical galaxy sample is needed, yet their morphology should be determined by laborious by visual inspections. In other large-scale surveys, early-type galaxies are selected by spectral features or by colour information, which excludes actively star forming galaxies from the sample (e.g., Bernardi et al. 2003; Eisenstein et al. 2003). Actively star forming elliptical galaxies are here reported in a bright galaxy sample, which was given morphologically classified by visual inspections, obtained from the Sloan Digital Sky Survey (SDSS; York et al. 2000).

## 2. The sample

The SDSS contains both photometric (Gunn et al. 1998; Hogg et al. 2001; Pier et al. 2003) and spectroscopic (Blanton et al. 2003) surveys, and produces the most homogeneous galaxy data set available to date. The initial SDSS observations were made in the northern and southern equatorial stripes, and produced a galaxy catalogue to  $r' = 22.5$  mag in five colour bands (Fukugita et al. 1996) with a photometric calibration using standard stars observed at USNO (Smith et al. 2002). Spectroscopic follow-up was made to 17.8 mag with accurately defined criteria for target selection (Strauss et al. 2002). The dominant part of these data has already been published as an *Early Data Release* (EDR) (Stoughton et al.

2002) and *Data Release One* (Abazajian et al. 2003). The sample is particularly useful to study statistical properties of field galaxies, which has traditionally been a difficult task.

The region of the sky we consider is the northern equatorial stripe (SDSS photometry run numbers 752 and 756) for  $145.15^\circ \leq \text{R.A.} \leq 235.97$  and  $|\delta| \leq 1.27^\circ$ , which is included in the EDR sample. The total area is 229.7 square deg. We take bright galaxies with  $r^* \leq 15.9$  mag after Galactic extinction corrections. This magnitude limit corresponds to the faintest galaxies for which reliable morphological classifications can be made by eye using SDSS imagery for essentially all objects. We have classified all galaxies satisfying this magnitude criterion in the northern equatorial stripe. The total number of galaxies is 1875, among which 1600 (85%) also have spectroscopic information. These galaxies have typical redshifts  $z \lesssim 0.12$ .

All galaxies in our sample (1875) are classified into one of seven morphological classes,  $T = 0$  (corresponding to E in the Hubble type), 1 (S0), 2 (Sa), 3 (Sb), 4 (Sc), 5 (Sd), and 6 (Im). Morphology classification was carried out by two of us (MF and ON) using the  $g'$  band image to enhance the galactic structure, according to *Hubble Atlas of Galaxies* (Sandage 1961). We assign an index of  $-1$  when the images are so disturbed that we cannot determine a morphological type. The classifications by MF and ON agree within  $\Delta T \leq 1.5$  for most galaxies and a mean of the two (0.5 step in  $T$ ) is taken as the final classification.

Among the 1600 galaxies in the spectroscopic subsample we obtain 210 E galaxies, 251 S0 galaxies and 169 galaxies for a class between E and S0, which may be either true E/S0 objects or galaxies which were classified as E by one person and S0 by the other. The physical properties of our E/S0 galaxies are in fact between the E and S0 samples as a whole. We impose a rather strict criterion for the selection of E galaxies that the galaxy shows no structure and is judged to be an elliptical galaxy by both classifiers, so that the sample does not contain contaminants from S0. We obtain 926 spiral and 23 irregular galaxies. 21 galaxies are left unclassified. The somewhat larger fraction of E-S0 galaxies (0.39) compared to the value ( $\approx 0.3$ ) usually adopted in the literature (e.g., Fukugita, Hogan & Peebles 1998) is due to our use of  $r'$  colour as the prime passband to make the galaxy catalogue.

### 3. Emission line galaxies in the elliptical galaxy sample

Among 210 E galaxies, 3 galaxies show  $H\alpha$  emission lines with the equivalent widths greater than  $10\text{\AA}$ , which is a typical value for star-forming spiral galaxies<sup>5</sup>. Among these three one galaxy is considered to be a Seyfert 2 galaxy due to strong  $[\text{OIII}]\lambda 5007$  emission. The other two either do not show  $[\text{OIII}]$  lines or show only weak  $[\text{OIII}]$  features, and are thus apparently actively star forming galaxies. This statement can be made more quantitative by employing the line diagnostics in the diagram of  $[\text{OIII}]/H\beta$  versus  $[\text{NII}]/H\alpha$  (Baldwin, Phillips, & Terlevich 1981; Velleux & Osterbrock 1987) with the criterion defined by Kauffmann et al. (2003) for the SDSS sample. We present the  $g'$  band images (in the logarithmic scale) and the spectra of the three galaxies in Figure 1 (the fourth panel shows a *bona fide* elliptical galaxy for comparison). The contrast is adjusted to emphasize the faintest level. We cannot detect any morphological differences among the four images. The spectroscopic features are conspicuously different. The first two show strong  $H\alpha$  emission, whereas  $[\text{OIII}]$  features are missing or weak. The spectra resemble those of late spiral or irregular galaxies with active star formation. The star formation rates are estimated to be  $3 - 5 M_{\odot} \text{ yr}^{-1}$  assuming the conventional transformation formula of Glazebrook et al. (1999) for the Salpeter initial mass function. The two galaxies have luminosities close to the characteristic value ( $M_{r^*} = 21.4 \text{ mag}$  at  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ), so they are *bona fide* ‘giant elliptical galaxies’. The third example shows strong  $H\alpha$  and  $[\text{OIII}]$  emission, typical of Seyfert 2 galaxies. The coordinates and the properties of these three galaxies are given in Table 1.

The inverse concentration indices as defined by the ratio of the radii that contain 90% and 50% of the Petrosian flux,  $c = r_{50}/r_{90}$ , are 0.39 and 0.33 for the two star forming galaxies. The former value is near the upper edge of the  $c$  parameter expected for elliptical galaxies (Shimasaku et al. 2001): see Figure 2, where the two galaxies are denoted by larger solid circles at  $T = 0$ . The colour of the two galaxies is significantly bluer than that of elliptical colours (Figure 3a). Therefore, this type of elliptical galaxy would be rejected in samples of early type galaxies constructed on the basis of colours, as in e.g., Eisenstein et al. (2003) and Bernardi et al. (2003). We find that the two galaxies are slightly bluer, by  $\Delta(g^* - r^*) = (g^* - r^*)_{3'' \text{ aperture}} - (g^* - r^*)_{\text{Petrosian}} \simeq -0.1$ , near their centers (observed with the  $3''$  aperture) than the mean (using Petrosian magnitudes), which is a reminiscent of with the blue core of higher redshift elliptical galaxies found by Menanteau et al. (2001). This contrasts to normal early type galaxies which show the opposite colour gradient  $\Delta(g^* - r^*) \simeq +0.05$ . It is also opposite to normal disc galaxies, for which the colour

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<sup>5</sup>There is one more elliptical galaxy that shows emission feature (photometry id in *EDR*: 752-4-8-9469-0046). Since there is a close companion to this galaxy, we remove it from our consideration.

gradient is  $\Delta(g^* - r^*) > 0$ . The two star forming galaxies are in the general field, not in clusters. The galaxy No. 2 (see Table 1) is in somewhat a rich environment in sky, but none in the vicinity has a comparable redshift.

As a check of the possibility that an error in the SDSS database was not responsible for the unusual association of spectra and morphology reported here, independent spectra of these two galaxies were obtained with the APO 3.5m telescope using the DIS instrument; the 3.5m data confirmed the presence of the strong emission lines in these objects. We conclude that 2 out of 210 elliptical galaxies show active star formation. The corresponding frequency is  $2/210=0.95\%$  in the entire sample of galaxies. These two galaxies have cores comparable to or slightly softer than ordinary elliptical galaxies.

We may extend this analysis to include E/S0 and S0 galaxies. We find that 19 out of 420 E/S0-S0 galaxies show  $H\alpha$  lines with equivalent widths of  $> 10\text{\AA}$ . This rate is significantly higher than that for elliptical galaxies alone. Comparisons of the concentration index and the colour are included in Figures 2 and 3 above. The distribution of the  $c$  parameter does not differ from that for normal S0 galaxies, but the  $g^* - r^*$  colour is significantly bluer for most of emission line S0 galaxies. The core is also bluer than the average colour by 0.05–0.1 mag. Including E galaxies, the frequency of star forming early type galaxies is 3.3% in the early galaxy sample, and 1.3% in the entire galaxy sample at  $z < 0.12$ .

If we include galaxies with Balmer emission of  $> 5\text{\AA}$  equivalent width, we add 4 galaxies in the E sample, and 4 galaxies in the E/S0-S0 sample. The fraction of early-type emission line galaxies in the total galaxy sample then becomes 1.8%.

#### 4. Discussion and Conclusions

There is a class of galaxies, so-called E+A galaxies (Dressler & Gunn 1983), which show spectral features of A-stars, such as strong Balmer absorption, superimposed on the old K-M star spectrum of early type galaxies. These galaxies are believed to be those which are within 1 Gyr after star formation ceased. There are a number of field galaxies that show the E+A feature (Zabludoff et al. 1996; Quintero et al. 2003; Goto et al. 2003). We have plotted *early-type galaxies* in the equivalent widths  $EW(H\alpha)$ - $EW(H\delta)$  plane in Figure 4. If we impose the criterion  $EW(H\delta) < -3\text{\AA}$  (minus means absorption) we are left with 15 galaxies, among which one (non AGN) S0 galaxy shows a strong  $H\alpha$  emission with  $EW(H\alpha) > 10\text{\AA}$ . We also see several galaxies which show  $H\alpha$  emission and at the same time significant  $H\delta$  absorption. These galaxies may be identified as transition cases in which star formation is currently declining. The unique feature of our analysis is that E+A galaxies are selected

from the visually identified E and S0 galaxy sample. This evidences the existence of E+A galaxies having early-type morphology, whereas evidence has been reported that some of E+A galaxies found in earlier literature are disc galaxies (e.g., Franx 1993; Caldwell et al. 1996).

The abundance of E+A galaxies depends on the selection criterion. If we use more strict criterion, as in Zabludoff et al. 1996,  $EW(H\delta) < -5.5\text{\AA}$ , the number decreases to 4. The fraction 0.25% in our sample is consistent with  $21/11113=0.19\%$  ( $0.05 < z < 0.13$ ) derived by those authors from the LCRS sample. Quintero et al. (2003) identified 1200 E+A galaxies in an SDSS sample of 156,000 galaxies (0.76%). This fraction is consistent with ours derived here, although the selection criteria are different.

Our fraction of E+A galaxies, 0.9%, (the number becomes 2.1% if we take  $EW(H\delta) < -2\text{\AA}$  as E+A galaxies) is on the same order of magnitude as that of emission-line early-type galaxies, although this comparison is admittedly qualitative.

We would suppose that the emission-line early-type galaxies studied here develop into E+A galaxies after star formation ceases, and further develop into normal early-type galaxies in a few gigayears. With this assumption the relative frequencies of star forming vs. E+A galaxies imply that early-type galaxies show star-formation activity for 1-2 Gyr, or at least not much less than 1 Gyr. Since the lookback time corresponding to our maximum sight,  $z \leq 0.12$ , 1.5 Gyr is comparable to the duration of star-formation activity, the star-formation activity once it took place below  $z = 0.12$  should be visible in our sample.

We do not ask the question how elliptical galaxies acquire star formation activity. If we would take the view of hierarchical galaxy formation that elliptical galaxies formed by merging processes, and if we identify star-forming early-type galaxies as new additions to the early-type galaxy population, the number of early-type galaxies increases with time. Assuming a power law for the number evolution  $N \sim (1+z)^{-\gamma}$  the increase is at a rate of  $N^{-1}(dN/dz)\Delta z \sim -\gamma\Delta z$  during the interval of  $\Delta z$  at  $z \approx 0$ , and we then obtain  $\gamma \approx 0.4$  for  $\Delta z \approx 0.068$ , the median redshift of our sample. This implies that the number density of early-type galaxies at  $z \approx 1$  is smaller than the present day value by 30%.

The slow evolution we derived may be compared with that of Im et al. (2002), who concluded a moderate decline of early-type galaxies in number by a few tens of percent at  $z \sim 1$  from their study of the luminosity function. The evolution of early-type galaxies we observed is significantly lower than that obtained by Kauffmann, Charlot & White (1996), who identified early-type galaxies by using a colour cut predicted in a passively evolving galaxy model and found the number density of early type galaxies at  $z = 1$  to be 1/2-1/3 the present value, which agrees with the evolution inferred in  $\Omega = 1$  CDM models. In a  $\Lambda$

cosmology, the evolution is slower at low redshifts; a 30% reduction is inferred (Kauffmann & Charlot 1998), which is consistent with our finding.

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Table 1: Elliptical galaxies with  $H\alpha$  emission lines (with equivalent width  $> 10\text{\AA}$ ).

| ID        | RA               | dec               | EW( $H\alpha$ )<br>( $\text{\AA}$ ) | $r^*$ | $g^* - r^*$ | $M_{r^*}$ | redshift | SFR<br>( $M_{\odot}\text{yr}^{-1}$ ) |
|-----------|------------------|-------------------|-------------------------------------|-------|-------------|-----------|----------|--------------------------------------|
| galaxy #1 | $12^h08^m23.5^s$ | $+0^\circ06'37''$ | 11.4                                | 14.79 | 0.63        | −21.49    | 0.041    | 2.9                                  |
| galaxy #2 | $11^h23^m27.0^s$ | $-0^\circ42'49''$ | 38.2                                | 15.48 | 0.55        | −20.79    | 0.041    | 4.8                                  |
| galaxy #3 | $10^h0^m08.4^s$  | $+0^\circ59'05''$ | 52.8                                | 15.87 | 0.49        | −19.82    | 0.031    | AGN                                  |

The luminosities are for  $H_0 = 70\text{km s}^{-1}\text{Mpc}^{-1}$ . For the star formation rate (SFR), the conversion factor of Glazebrook et al. (1999) [model BC96(kl96)] is assumed.

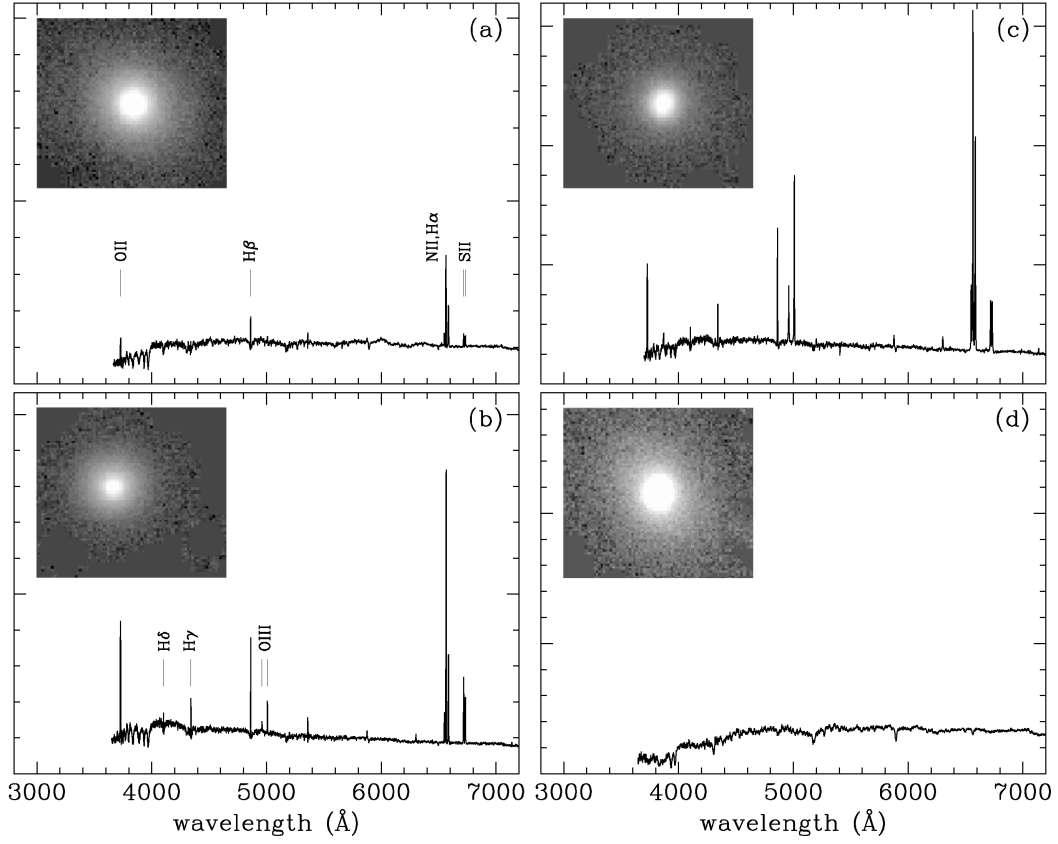


Fig. 1.—  $r'$  band images and spectra. (a) and (b) elliptical galaxies (galaxy #1, and #2) with strong H $\alpha$  emission lines, where emission lines dominantly arise from star formation, (c) H $\alpha$  emission-line elliptical galaxy with AGN activity (galaxy #3), and (d) normal elliptical galaxy for comparison. The identifications are those given in *EDR*.

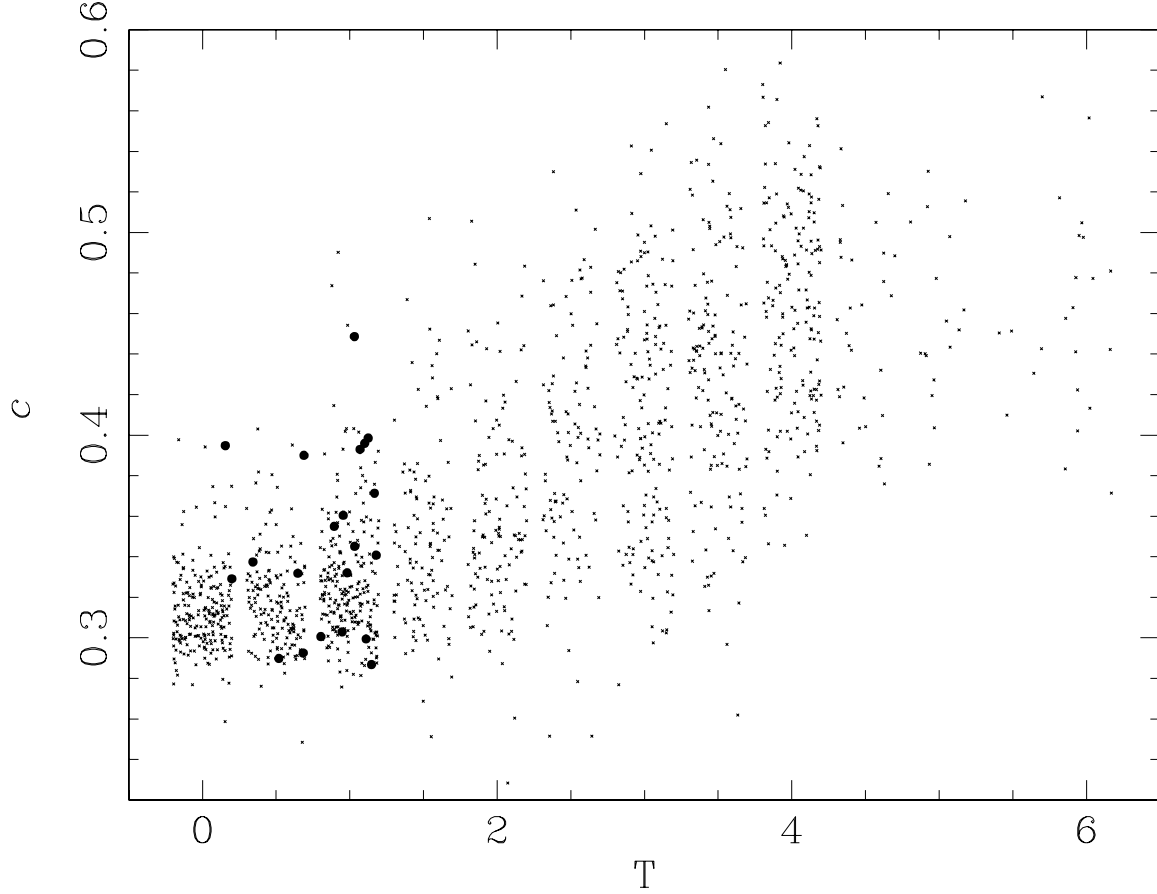


Fig. 2.— Inverse concentration parameters  $C$  of morphologically classified galaxies. Morphological classes are  $T = 0$  (E), 1 (S0), 2 (Sa), 3(Sb), 4(Sc), 5(Sd) and 6(Im) allowing for those in between (with  $\Delta T = 0.5$  step). Strong  $H\alpha$  emission line galaxies of early types are denoted by larger circles. We make the bins somewhat smeared to avoid clutter of the data.

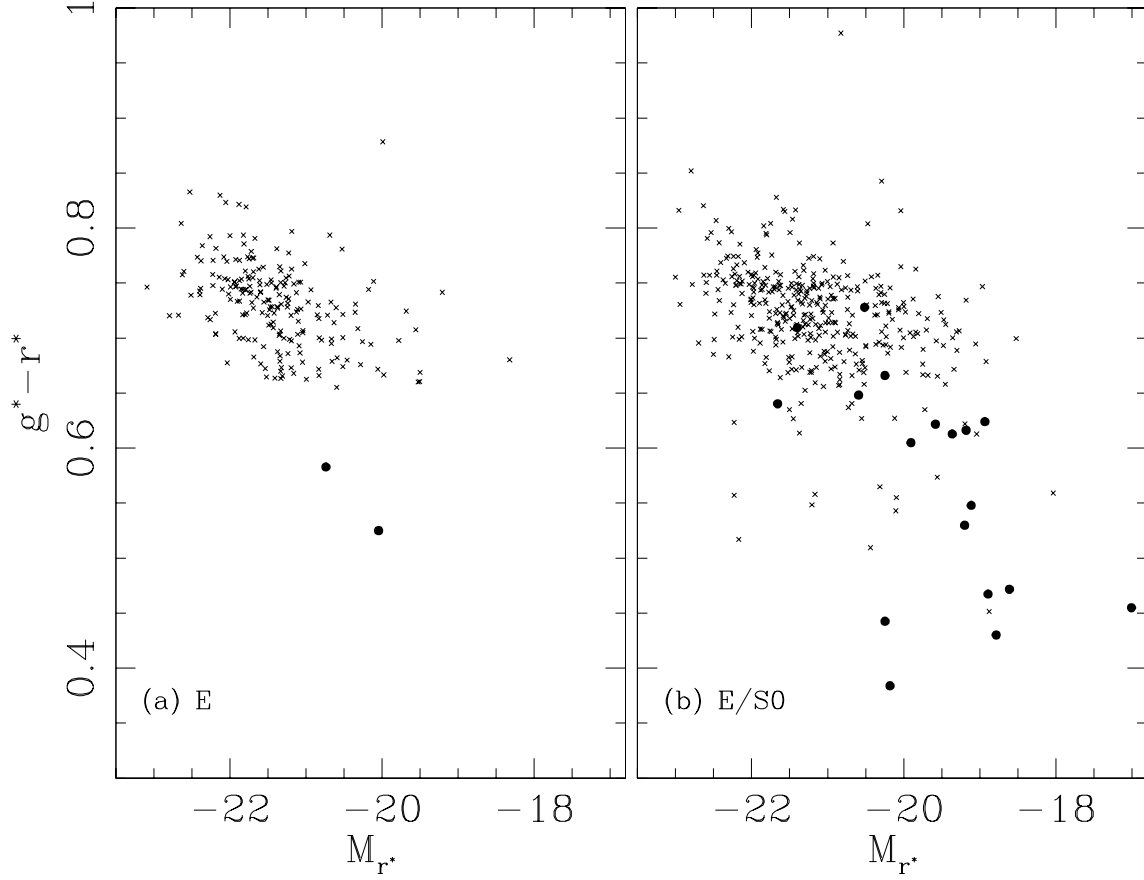


Fig. 3.— Colour magnitude diagram of early-type galaxies: (a) elliptical galaxies, and (b) E/S0 and S0 galaxies. Galaxies that show strong H $\alpha$  emission are denoted by large circles. The subscript  $g$  stands for the Petrosian magnitude.

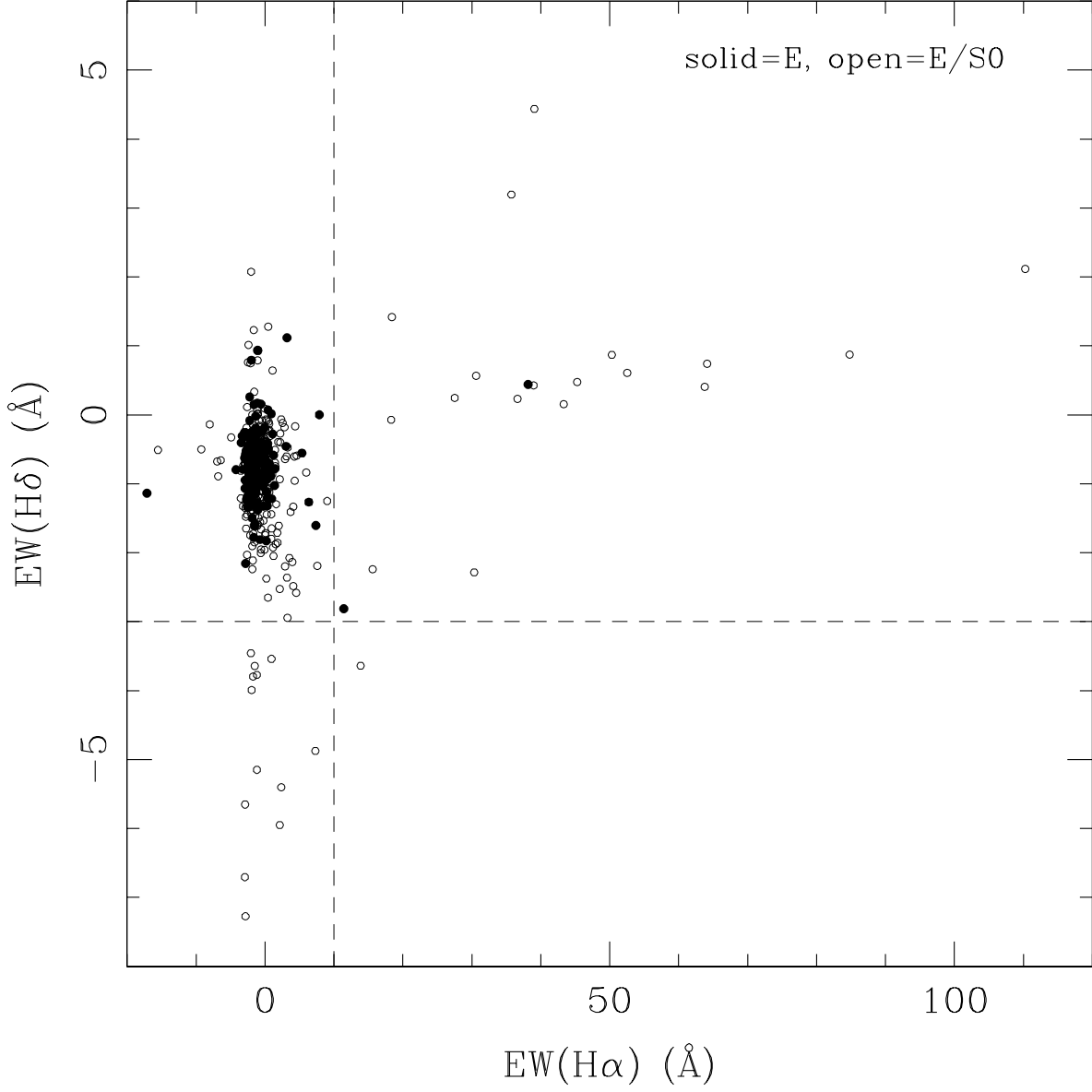


Fig. 4.— Distribution of early-type galaxies in the  $\text{EW}(\text{H}\alpha)$ – $\text{EW}(\text{H}\delta)$  plane. Solid circles denote elliptical galaxies, and open circles are E/S0 to S0 galaxies. Two dotted lines show the boundaries of  $\text{EW}(\text{H}\alpha) > 10 \text{ \AA}$  (strong emission-lines), and  $\text{EW}(\text{H}\delta) < -3 \text{ \AA}$  (strong Balmer absorption features).